Enhanced cosmic-ray ionization toward ζ Persei inferred from storage ring measurement of dissociative recombination rate of rotationally cold H₃⁺

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Too Much H$_3^+$ in Diffuse Clouds

- Column density $3 \times 10^{14}$ cm$^{-2}$, just like dense cloud!
- Chemical model $\rightarrow$ $n$(H$_3^+$) $\sim$ $10^{-7}$ cm$^{-3}$
- $N$(H$_3^+$) / $n$(H$_3^+$) $\rightarrow$ path length is 1 kpc!?
- Implies $\langle n$(H)$\rangle$ $\sim$ 20 cm$^{-3}$ (too low)

McCall, Geballe, Hinkle, & Oka
Science 279, 1910 (1998)
Other Diffuse Clouds, too!

- General problem with model:

$$[H_3^+] = \frac{\zeta}{k_e} \frac{N(H_2)}{N(e^-)}$$

- $\zeta$
- $k_e$
- $[H_2]/[e^-]$
$\text{H}_3^+$ toward $\zeta$ Persei

Rules out $[\text{e}^-]/[\text{H}_2]$
H$_3^+$ Dissociative Recombination

- Laboratory values of $k_e$ varied by 4 orders of magnitude!
- Even worse: theory in infancy, way off...
- Big problem: not measuring H$_3^+$ in ground states
Storage Ring Measurements

- Complete vibrational relaxation
- Very simple experiment
- Control $H_3^+$ – $e^-$ impact energy
- Rotationally hot ions produced
- No rotational cooling in ring

$H_3^+$

$H, H_2$

CRYRING
• $\text{H}_3^+$ produced is rotationally cold, as in interstellar medium

CRYRING Results

• Structure (resonances) in the cross-section
• $k_e = 2.6 \times 10^{-7}$ cm$^3$ s$^{-1}$
• Chris Greene's theory

McCall, et al.
Nature 422, 500 (2003)
Implications for ζ Persei

\[ \frac{N(H_3^+)}{L} = [H_3^+] = \frac{\zeta N(H_2)}{k_e N(e^-)} \]

\[ \zeta L = (2.6 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1}) \frac{N(H_3^+)}{N(H_2)} \frac{N(e^-)}{(3.8 \times 10^{-4})} \]

\[ \zeta L = 8000 \text{ cm s}^{-1} \]

Adopt \( \zeta = 3 \times 10^{-17} \text{ s}^{-1} \)
\( L = 85 \text{ pc} \)
\( \langle n \rangle = 6 \text{ cm}^{-3} \)

Cross out:
Adopt \( L = 2.1 \text{ pc} \)
\( \zeta = 1.2 \times 10^{-15} \text{ s}^{-1} \)
(40x higher!)
• Enhanced cosmic-ray flux in $\zeta$ Persei
• Widespread $H_3^+$ in diffuse clouds
  – perhaps widespread cosmic-ray enhancement?
• Dense cloud $H_3^+$ is "normal"
  – enhanced cosmic-ray flux only in diffuse clouds
  – low energy component?
  – no constraints, aside from chemistry!!
• Substantial impact on diffuse cloud chemistry
  – more frequent ion-neutral reactions
  – enhanced oxygen chemistry ($H^+ + O \rightarrow O^+ + H$)
Future Work

• Search for H$_3^+$ in more UV-accessible sightlines
  – "Direct" probe of cosmic-ray flux
  – [Non-detections in $\omega$ Persei, $\zeta$ Ophiuchi ?]

• Observations of H$_3^+$ in heavily reddened sources
  – Fall-off in cosmic-ray flux
  – Transition of C$^+$ $\rightarrow$ CO

• Comprehensive study of $\zeta$ Persei
  – Review all constraints on density, path length
  – Model cloud structure, inhomogeneities
Rich Diffuse Cloud Chemistry

- From 1930s through the mid-1990s, only diatomic molecules thought to be abundant in diffuse clouds
- Since 1998, many polyatomics observed:
  - $\text{H}_3^+$ in infrared
  - $\text{HCO}^+, \text{C}_2\text{H}, \text{C}_3\text{H}_2$ in radio (Lucas & Liszt)
  - $\text{C}_3$ in near-UV (Maier, et al.)
- Diffuse Interstellar Bands!